

## Sigma-delta modulator

The present invention relates generally to a sigma-delta modulator and method thereof.

5                Figure 1A shows the structure of a conventional digital feedback Sigma Delta Modulator (SDM) 10. As shown, the output signal 20 of the quantizer 12 is fed back over the weights (or gains)  $a_{1...n}$  ( $n \geq 1$ ) and subtracted from the integrator  $I_{1...n}$  inputs. Figure 1B shows the structure of a conventional digital feed forward Sigma Delta Modulator (SDM) 11. As shown, the outputs of the integrators  $I_{1...n}$  are weighted and  
10                summed (in summer 13). The output signal 20 of the quantizer 12 is fed back and subtracted from the input to the first integrator.

                 As long as the SDM 10 is stable, the values of the integrators  $I_{1...n}$  are bounded. However, higher order (for example, above 2nd order) SDMs (in particular, 1-bit SDMs) are unstable for large input signals. This phenomenon may cause problems in Sigma  
15                Delta Analog to Digital Converters (ADCs) and Digital to Digital (DD) converters, because the input signal amplitude cannot be controlled (for example, in a live recording). Existing solutions to stabilize an SDM rendered unstable due to a large input are described below.

                 A characteristic of an unstable SDM is that the output signal 20 includes long strings of 0's or 1's. If long strings of equal outputs are detected, the SDM 10 may be reset. A  
20                disadvantage of this solution is that the output bitstream of the SDM 10 will contain a discontinuity which is very audible.

                 Another conventional solution, as taught in Tewksbury et al. "Oversampled, Linear Predictive, and Noise-Shaping Coders of Order  $N > 1$ ", IEEE Transactions on Circuits and Systems, Vol. 25, July 1978, includes the use of clippers. Just before a SDM becomes  
25                fully unstable, the value of the internal integrators increases quickly. By applying a limiter circuit to the values of the integrator  $I_{1...n}$ , the SDM 10 maintains stability. However, the stability is, in general, not unconditional and is only guaranteed for values slightly above the normal range of operation. When the clippers are active, the SNR degrades, dropping to low

levels quickly. Further, the clippers also slightly degrade the SNR in the original stable useable area. Still further, the activation of clippers often leads to audible artifacts.

As described, conventional techniques for maintaining SDM stability have at least three disadvantages:

- 5                   1. stability is not unconditional,
2. SNR performance is degraded, and
3. audible artifacts are introduced.

10                   An object of the invention is to present a solution that improves the stability of a sigma-delta modulator (SDM).

                  To this end, the present invention provides a unit that includes  $n$  ( $n \geq 1$ ) integrators in series, where a first of the  $n$  integrators receiving an input signal, at least one Q device, which acts as a quantizer when an absolute value of a signal input thereto is smaller  
15                   and as a gain element when the absolute value of the signal input thereto is larger, and a device for quantizing an output of the unit.

                  In one or more exemplary embodiments, the unit is a feed back or feed forward SDM.

                  In one or more exemplary embodiments, the unit includes one Q device. In  
20                   such an arrangement, the one Q device may be positioned so that the signal input to the one Q device is an output of the last integrator and the output of the one device  $Q_1$  is input to the device for quantizing and/or to the feedback loops with weights to the  $n$  integrators.

                  In one or more exemplary embodiments, the unit includes  $m$  Q devices (where  $m \leq n$ ). In such an arrangement, the signal input to the  $m$  Q devices, may be an output of the  
25                   last integrator, the outputs of the  $m$  Q devices may be input to one or more of the  $n$  feedback loops with weighting to the integrators, and the output of the last integrator or the output of any of the  $m$  Q devices is input to the device for quantizing.

                  In an alternate arrangement, the signals output from the  $n$  integrators are weighted and summed, the summed output is input to the  $m$  devices, outputs of the  $m$  Q  
30                   devices are input to one or more of the  $n$  integrators, and an output of one of the  $m$  Q devices is input to the device for quantizing.

                  In another alternate arrangement, the signals output from the  $n$  integrators are weighted and summed, the summed output is input to the  $m$  Q devices and the device for quantizing, and outputs of the  $m$  Q devices are input to one or more of the  $n$  integrators.

The exemplary units of the present invention may be components of an analog to digital converter and/or a digital to digital converter. The exemplary units of the present invention may process digital or analog signals, for example, a 1-bit signal.

5 In the exemplary embodiments with more than one Q device, each of the Q devices may have different parameters set to improve stability, improve SNR, and/or reduce introduction of artifacts.

Exemplary embodiments of the present invention may also be directed to a method including inputting a signal to  $n$  ( $n \geq 1$ ) integrators  $I_{1...n}$  in series, quantizing when an absolute value of a signal input thereto is smaller and amplifying when the absolute value of  
10 the signal input thereto is larger, and quantizing an output.

Other objectives of the invention are to present a solution that improves the SNR performance of an SDM and/or reduce audible artifacts, such as clicks and pops.

15 The present invention will become more fully understood from the detailed description given below and the accompanying drawings, which are given for purposes of illustration only, and thus do not limit the invention.

Figure 1A shows the structure of a conventional feedback SDM.

Figure 1B shows the structure of a conventional feed forward SDM.

20 Figure 2 shows the structure of a feedback SDM in accordance with an exemplary embodiment of the present invention.

Figure 3 shows a generic transfer function of the device Q in accordance with an exemplary embodiment of the present invention.

25 Figure 4 shows the structure of a feedback SDM in accordance with another exemplary embodiment of the present invention.

Figure 5 shows the resulting spectrum of an SDM structure in accordance with an exemplary embodiment of the present invention for an input sine of 1kHz with amplitude 0.7.

30 Figure 6 shows the resulting spectrum of an SDM structure in accordance with an exemplary embodiment of the present invention for an input sine of 1kHz with amplitude 0.8.

Figure 7 shows the structure of a feed forward SDM in accordance with an exemplary embodiment of the present invention.

Figure 8 shows the structure of a feed forward SDM in accordance with another exemplary embodiment of the present invention.

Figure 9 shows the structure of a feed forward SDM in accordance with another exemplary embodiment of the present invention.

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Figure 2 shows the structure of a feedback SDM 100 in accordance with an exemplary embodiment of the present invention. The exemplary embodiment reduces or prevents uncontrolled growth of integrator  $I_{1...n}$  values (an indicator of instability) by replacing the conventional quantizer (for example a 1-bit quantizer) with a device Q that acts as a normal quantizer for smaller inputs, but acts as a gain element with offset (equal to or different from zero) for larger inputs. As shown in Figure 2, the output of the device Q is used as feed back signal to the gains  $a_{1...n}$ . The final output is created by also quantizing the output of the last integrator using a normal quantizer.

Figure 3 shows an example generic transfer function of the device Q in accordance with an exemplary embodiment of the present invention. The generic transfer function may be defined as follows:

for small positive inputs (range  $[0, r]$ ) the output is equal to  $t$ ;  
 for large positive inputs (range  $\langle r, \text{inf} \rangle$ ) the output is  $t + (x-r) \cdot s$ ;  
 for small negative inputs (range  $[-r, 0]$ ) the output is equal to  $-t$ ; and  
 for large negative inputs (range  $\langle -\text{inf}, -r \rangle$ ) the output is  $-t + (x+r) \cdot s$ .

Exemplary values for the parameters may be  $r \in [1, 2]$ ,  $s \in [0, 10]$ ,  $t \in [0, 1]$ .  
 If  $s=0$  and  $t=1$ , the behavior is equal to that of a conventional 1-bit quantizer 12. For  $s \neq 0$ , the output of the device Q is not a 1-bit signal, but a multi-bit signal.

By choosing proper values for  $r$ ,  $s$ , and  $t$ , SDM 100 performance can be improved. With the exemplary structure of Figure 2, it is possible to create an SDM that is unconditionally stable (sustained inputs with an amplitude of 0 dB compared to the output level of the quantizer 12 will not drive the SDM 100 unstable).

Figure 4 shows the structure of a feedback SDM 200 in accordance with another exemplary embodiment of the present invention. The SDM 200 includes devices  $Q_{1...m}$ . In the exemplary embodiment of Figure 4, each of the devices  $Q_{1...m}$  may have different settings. This makes it possible to have

1. an unconditionally stable SDM - by choosing the parameters of the different devices  $Q_{1...m}$  appropriately, the SDM can be made with improved SNR; and/or
2. an SDM with improved or optimized SNR for a limited input range - the SNR can be improved or optimized for a given input range while outside the given input range, the SDM becomes unstable.

Whereas conventional techniques such as clippers, degrade the SNR already in the original stable regime, the exemplary embodiments of the present invention do not necessarily pose this drawback. In the normally unstable regime, the SNR performance can remain very high and fall off only slowly until instability is reached.

Clicks and pops are avoided. A further possibility is the stabilization of higher order (7 or higher) SDMs, which turn instable when clippers are active.

#### EXAMPLE 1

An example SDM with the structure of Figure 2 has been created. The SDM is a 5th order, 64 times oversampled ( $64 \cdot 44100$  Hz), with corner frequency 100 kHz (butterworth highpass design). The coefficients  $a_{1...5}$  are 0.719981, 0.252419, 0.052997, 0.006604, and 0.000389. The device Q has normal quantizer behavior for inputs between  $-1.5$  and  $1.5$  ( $r=1.5$ ). The slope  $s$  of the device Q is 0.9. Q has  $t=1.0$ .

Table 1 shows the achieved SNR for various sine inputs (sine frequency 1kHz) for both a conventional SDM (without the device Q) and the SDM structure in accordance with the exemplary embodiment of Figure 2 (with the device Q). Whereas the conventional SDM becomes unstable for inputs of 0.65 and higher, the SDM structure in accordance with the exemplary embodiment of Figure 2 is unconditionally stable. The performance of the SDM structure in accordance with the exemplary embodiment of Figure 2 is equal to the conventional SDM for inputs up to 0.65. Above inputs of 0.65 the SNR drops. Figure 5 shows the resulting spectrum of the SDM structure in accordance with the exemplary embodiment of Figure 4 for an input sine of 1kHz with amplitude 0.7.

TABLE 1

Input Amplitude	SNR (dB) (conventional quantizer)	SNR (dB) (Figure 2 embodiment)
0.1	85.41	85.41
0.2	90.20	90.20
0.3	95.63	95.63
0.4	97.60	97.60
0.5	100.05	100.05
0.6	100.54	100.54
0.64	101.96	101.96
0.65	101.33	101.33
0.66	0	67.40
0.7	0	44.72
0.8	0	25.30
0.9	0	23.18
1.0	0	21.98

## EXAMPLE 2

In this example the SDM is a 5th order, 64 times oversampled ( $64 \times 44100$  Hz), with corner frequency 80 kHz (butterworth high-pass design). The coefficients  $a_{1..5}$  are 0.576107, 0.162475, 0.027609, 0.002805, and 0.000136. Devices  $Q_1$ ,  $Q_2$  and  $Q_3$  have normal quantizer behavior for inputs between -1 and 1 ( $r=1$ ). Devices  $Q_4$  and  $Q_5$  have  $r=1.1$ . The slopes of devices  $Q_{1..5}$  are 1.5, 1.4, 0.45, 0.1, and 0.1. The parameter  $t$  of devices  $Q_{1..5}$  is 1.0. Table 2 lists the obtained SNR for sine inputs with frequency 1000 Hz. The first column lists the input amplitude. The second column shows the performance of the conventional quantizer, the third column, the performance with devices  $Q_{1..5}$ .

By using well chosen parameters for the different  $Q_{1..5}$ , (or in the generic case, for  $Q_{1..m}$ ) it is possible to reduce the effective order of the SDM for high input amplitudes. Figure 6 shows the power spectrum of the SDM structure in accordance with the exemplary embodiment of Figure 4 for an input sine of 1 kHz with amplitude 0.8. The low frequency part of the spectrum has 2nd order behavior, the high frequency part is 5th order. The exact frequency where the behavior changes from 2<sup>nd</sup> to 5<sup>th</sup>, is dependent on the input amplitude.

Although difficult to quantitatively express, perceived audio quality is very important. In the case of conventional clippers perceived audio quality degrades very fast in the original unstable area. The SDM structure in accordance with the exemplary embodiment of Figure 4 maintains much better audio quality in this region.

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TABLE 2

Input Amplitude	SNR (dB) (conventional quantizer)	SNR (dB) (Figure 4 embodiment)
0.1	77.15	77.15
0.2	83.76	83.76
0.3	87.58	87.58
0.4	89.62	89.62
0.5	91.59	91.59
0.6	95.44	95.44
0.7	95.29	95.29
0.8	0	76.73
0.9	0	66.68
1.0	0	38.60

As described and illustrated above, Figures 2 and 4 are both directed to feedback SDMs. As shown, a feedback SDM may include  $n$  integrators in series, where the output of the last integrator is input to a quantizer. The output of the quantizer is the SDM output and is subtracted from the input signal. The signal, which is the difference between the input signal and the quantizer output, is input to the first integrator.

However, the present invention may be applied to other SDMs, such as feed forward SDMs. A feed forward SDM may include  $n$  integrators in series, where the output of each integrator is weighted and summed. The sum is input to a quantizer and the output of the quantizer is the SDM output. The signal, which is the difference between the input signal and the quantizer output, is input to the first integrator.

Figure 7 shows the structure of a feed forward SDM 101 in accordance with an exemplary embodiment of the present invention. The exemplary embodiment reduces or prevents uncontrolled growth of integrator  $I_{1...n}$  values (an indicator of instability) by replacing the conventional quantizer (for example a 1-bit quantizer) with a

device Q that acts as a normal quantizer for smaller inputs, but acts as a gain element with offset (equal to or different from zero) for larger inputs. As shown in Figure 7, the output of the device Q is output to the quantizer and subtracted from the input to the first integrator. The final output of the SDM 101 is created by also quantizing the output of the last integrator using a normal quantizer 12.

By choosing proper values for r, s, and t, SDM 101 performance can be improved. With the exemplary structure of Figure 7, it is possible to create an SDM that is unconditionally stable (sustained inputs with an amplitude of 0 dB compared to the output level of the quantizer 12 will not drive the SDM 101 unstable).

Figure 8 shows the structure of a feed forward SDM 201 in accordance with another exemplary embodiment of the present invention. The SDM 201 includes devices  $Q_{1...m}$ . In the exemplary embodiment of Figure 8, each of the devices  $Q_{1...m}$  may have different settings. Exemplary values for t are 0.0 and 1.0. As shown in Figure 8, the output of the summer 13 is input to each of the devices  $Q_{1...m}$ . The output of the devices  $Q_{1...m}$  are subtracted from one or more of the integrators  $I_{1...n}$ . The output of one of the devices  $Q_{1...m}$  or summer 13 is also input to the quantizer 12 to produce the output signal 20.

Figure 9 shows the structure of a feed forward SDM 301 in accordance with another exemplary embodiment of the present invention. The SDM 301 includes devices  $Q_{1...m}$ . In the exemplary embodiment of Figure 9, each of the devices  $Q_{1...m}$  may have different settings. As shown in Figure 9, the output of the summer 13 is input to each of the devices  $Q_{1...m}$  and the also input to the quantizer 12 to produce the output signal 20.

As described and illustrated above, Figures 2, 4, 7, 8, and 9 illustrate digital SDMs. However, the present invention may be applied to analog SDMs (either feed back or feed forward).

It is further noted that the features of the present invention are usable with many types of SDMs and noise shapers, including feedback, feed forward, continuous, discrete time, software, hardware, analog, digital, SC-filter, dithered, undithered, low order, high order, single-bit, multi-bit or any combination of these features, as well as other devices such as noise shapers, either in combination (for example, cascaded) with SDMs and/or other devices or alone.



It is further that the structural and functional features of the various exemplary embodiments described above may be used interchangeably, individually or in combination. For example, the quantizer 12 could also be any known quantizer equivalent.

The device according to embodiments of the invention may be included in an  
5 ADC and/or DD converter. Such an ADC and/or DD converter may be part of signal processing applications/devices for Super Audio CD (SACD) equipment, e.g. a player.

It is noted that the processing described above is particular useful in the processing of DSD.

It is further noted that that the input need not be restricted to a bitstream; the  
10 input may be analog or digital. It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative embodiments without departing from the scope of the appended claims. In the claims, any reference signs placed between parentheses shall not be construed as limiting the claims. The word "comprising" does not exclude the presence of other elements or steps  
15 than those listed in a claim. The modifiers "a", "an", "one" and "at least one" as used in the appended claims all are intended to include one or more of whatever they modify. The invention can be implemented by means of hardware comprising several distinct elements, and by means of a suitable programmed computer. In a device claim enumerating several means, several of these means can be embodied by one and the same item of hardware. The  
20 mere factor that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.